AD-A186 407 LASER THERMAL PROPULSION(U) TENNESSEE UNIV SPACE INST 1/1
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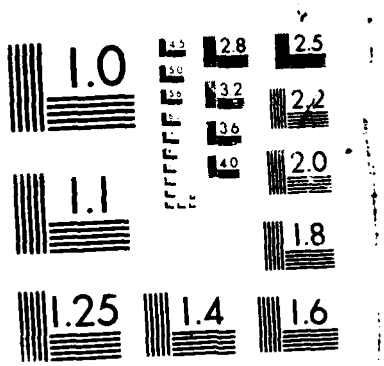

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The objective of this research investigation was to determine, experimentally and analytically, the physical mechanisms that control the behavior of continuous, laser sustained plasmas (LSP). The principal questions involve the effects of a forced convection environment and optical geometry on the stability, fractional power absorption, plasma structure, and fluid mixing.

A continuous, 1.5 kW, axial flow, carbon dioxide laser was used to create the LSP in a cylindrical quartz flow channel. The convection flowfield surrounding the plasma was controlled by the volume flow through the test chamber, and the optical geometry was determined by the unstable oscillator output mode of the laser and the focal length of the lens. Digital images of the plasma in a selected narrow wavelength interval were obtained using a CID digital camera and a VICOM digital image processing computer that were calibrated for absolute radiance. These images were then Abel inverted to give a spatial plasma emission coefficient which determined the spatial distribution of the plasma temperature. These measured

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19. **Abstract** (Continued):

temperature fields were then used to calculate the laser power absorption in the plasma and the power lost from the plasma through optically thin emission. More than one hundred sets of data were obtained for argon plasmas at nominal pressures from 1.5 to 3 atmospheres and incident flow velocities from Ø.4 to 4.Ø m/s.

Detailed examination of the complex interactions of the various energy absorption and loss mechanisms was aided by the development of a computer model for the LSP. The computer model is based on a laminar Navier-Stokes description of the flow and a geometric ray trace description of the laser beam propagation through the optics and the plasma. It was found that the LSP was stable in the presence of significant convective flow environments, and that the plasma radiation and fractional power absorption could be controlled by appropriate combinations of pressure, optical geometry and flow.

FINAL REPORT

Objective

The principal objective of this research was to determine the effects of a forced convection flow environment on the stability, fractional power absorption, flow structure and mixing in a laser sustained plasma (LSP).

Approach

Detailed experimental measurements of the plasma temperature field were obtained which could then be used to analyze the spatially resolved energy and momentum balance within the LSP. The detailed spatial analysis was greatly aided by the development of a new computational model for the LSP [1].

The plasma absorption mechanism, inverse bremsstrahlung, is applicable at all potential laser wavelengths, but the UTSI experiments utilized a 1.5 kW carbon dioxide laser to take advantage of the long run times, good beam quality, and ease of operation. Argon was used as the plasma medium since it is easily sustained with moderate laser power and provides for a relatively large range of pressures and flow rates for the available laser power. Experimental results can be extrapolated to other gases and laser wavelengths through the known relationships between wavelength and absorption coefficient for inverse bremsstrahlung.

The temperature field in the plasma was measured using narrow wavelength bandpass images of the plasma emission acquired with a VICOM digital image processing computer and a CID video camera. The entire measurement system was calibrated using direct substitution of an absolute radiance standard lamp. The resulting images were converted to emission coefficient values within the plasma through the use of a new transform method of Abel inversion [2] that was developed to treat the large quantities of data accurately and efficiently. The emission coefficients were then related to the plasma temperature using the assumption of local thermodynamic equilibrium and the known relationships between plasma continuum emission coefficients and the plasma temperature and pressure. The overall experimental configuration is shown in Figure 1, and these techniques were described in detail in several publications [3,4,5].

The spatially resolved absorption of power from the laser beam and the power lost from the plasma through emission was calculated using the measured temperature fields. The input power distribution of the laser beam incident on the lens was described by a series of rays, each carrying a prescribed fraction of the laser power. These rays were then traced through the optical elements (lens and window) and then through the measured plasma temperature field. At each computational step through the plasma, a new ray direction was calculated based on the temperature dependent index of refraction of the plasma. Then, the power absorbed by the plasma from the laser beam, the attenuation of

the beam and the power radiated from the plasma were all calculated for that spatial volume based on the local temperature. Using this technique, both the global and spatially resolved energy balance of the plasma could be obtained. Results from this analysis of the experimental data were published in References [3,4,5]. A major result of this work was the determination that the LSP was stable in the presence of substantial flow, and an understanding of the degree to which the optical geometry controlled the behavior of the LSP.

In order to better understand the effects of the optics on the operation of the LSP, a Fourier optics method was developed to study the optical intensity near focus that results from a combination of lens aberration and diffraction. This new technique was implemented on the VICOM image processing computer where the large number of Fourier transforms could be computed efficiently, and the results of the calculations could be displayed as images for ease of interpretation. The details of this new technique have been published in References [3,4]. It was found that the combined effects of spherical aberration and diffraction greatly altered the distribution of optical intensity in the focal volume, when compared with simple paraxial ray analysis, for the unstable oscillator annular beam used in the experiments.

The analytical models that were available for comparison with the detailed experimental results were limited. The models were either one-dimensional or had used simplifying assumptions for the temperature dependent plasma properties or the radial components of the flow. A new model was developed for the LSP based on the laminar Navier-Stokes equations to describe the flow, and a geometric ray trace through the optics to describe the propagation of the laser beam through the plasma. A computer code was developed using the SIMPLE algorithm to solve the equations. The computer model was verified using the detailed experimental data, and was found to give good predictions of plasma temperature, position within the focal volume, response to flow changes and global values of the power absorption and radiation when the plasma pressure was greater than 2 atmospheres. Having verified the computer model using the experimental data for argon plasmas, the code was modified to obtain predictions for plasmas sustained in hydrogen, the propellant of interest for high specific impulse rockets. The development of the computer model, the verification using the measured data and the calculations for hydrogen have been published in References [1,6,7].

The principal accomplishments of this research were:

- Detailed experimental measurements of plasma temperature for plasmas sustained in a forced convection flow.
- Development of new transform techniques for the accurate and efficient Abel inversion of large quantities of data.
- Development of new Fourier optical methods to calculate the intensity near focus for combined lens aberration and diffraction.
- Development of a comprehensive computer model to predict the characteristics of laser sustained plasmas.

Some important conclusions can be drawn from this research regarding the laser sustained plasma and its suitability for an advanced propulsion system. It was found that the LSP could operate in a highly stable manner over a wide range of pressure and flow conditions. It was found that the fractional power absorption of the laser beam and the radiation losses from the plasma could be controlled using a combination of laser power, optical geometry, pressure and flow. Computer calculations indicate that for laser powers greater than a few tens of kilowatts, the absorption of the laser beam by a hydrogen plasma approaches 100%, and that the radiation losses from the plasma could be used efficiently in a regenerative cycle to provide a specific impulse in excess of 1500 sec. There do not appear to be any "fatal flaws" in the concept for using the laser sustained plasma as a means to absorb energy from a laser beam and heat a suitable propellant gas, and further studies regarding the use of beamed laser power for propulsion are warranted.

There remain some questions that deserve further study. In particular, the characteristics of plasmas sustained with Gaussian profile beams, and the characteristics of plasmas sustained with lasers having different wavelengths and pulsed power formats, such as the free electron lasers.

Professional Personnel

1. Dr. Dennis Keefer, Professor of Engineering Science and Mechanics.
2. Dr. Carroll Peters, Professor of Aerospace and Mechanical Engineering.
3. Dr. San-Mou Jeng, Research Engineer.
4. L. Montgomery Smith, Engineer.
5. Herbert Crowder, Engineer.
6. Newton Wright, Engineer.

Interactions

There was a close and continuing role as advisor and consultant between Drs. Keefer and Peters with the Laser Propulsion project at NASA Marshall Space Flight Center. This interaction involves the diagnostics, ignition, and data analysis for experiments in laser sustained hydrogen plasmas and experimental design and preliminary experimentation on water vapor absorption in carbon dioxide laser beams. The project director at NASA/MSFC was Dr. T. Dwayne McCay.

The following papers have been presented at national meetings:

1. Keefer, D., Peters, C., and Crowder, H., "A Reexamination of the Laser Supported Combustion," AIAA Thermophysics Conference, Montreal, Canada, in June 1983.

2. Keefer, D., Crowder, H. and Peters, C., "Laser Sustained Argon Plasmas in a Forced Convection Flow," AIAA 23rd Aerospace Sciences Meting, Reno, Nevada, January 1985.

3. Keefer, D., Welle, R. and Peters, C., "Power Absorption Processes in Laser-Sustained Argon Plasmas," AIAA18th Fluid Dynamics and Plasmadynamics and Laser Conference, Cincinnati, Ohio, July 1985.

4. Welle, R. P. and Keefer, D. R., "Imagining of Continuum Emission for Diagnostics of Laser Sustained Plasmas," 1st International Laser Science Conference, Dallas, Texas, November 1985.

5. Welle, R., Keefer, D. and Peters, C., "Energy Conversion Efficiency in High-Flow Laser-Sustained Argon Plasmas," AIAA/ASME 4th Fluid Mechanics, Plasma Dynamics and Lasers Conference, Atlanta, Georgia, May 1986.

6. Jeng, S. M., Keefer, D. R., Welle, R., and Peters, C., "Numerical Study of Laser-Sustained Argon Plasmas in a Forced Convective Flow," AIAA/ASME 4th Fluid Mechanics, Plasma Dynamics and Lasers Conference, Atlanta, Georgia, May 1986.

7. Jeng, S. M. and Keefer, D. R., "Numerical Study of Laser-Sustained Hydrogen Plasmas ina Forced Convective Flow," AIAA/ASME/SAE/ASEE 22nd Joint Propulsion Conference, Huntsville, Alabama, June 1986.

8. Smith, L. Montgomery and Keefer, Dennis R., "The Fourier Optical Analysis of Aberrations in Focused Laser Beams," *Spie's 3Øth Annual International* Technical Symposium, San Diego, California, Aug. 1986.

Inventions

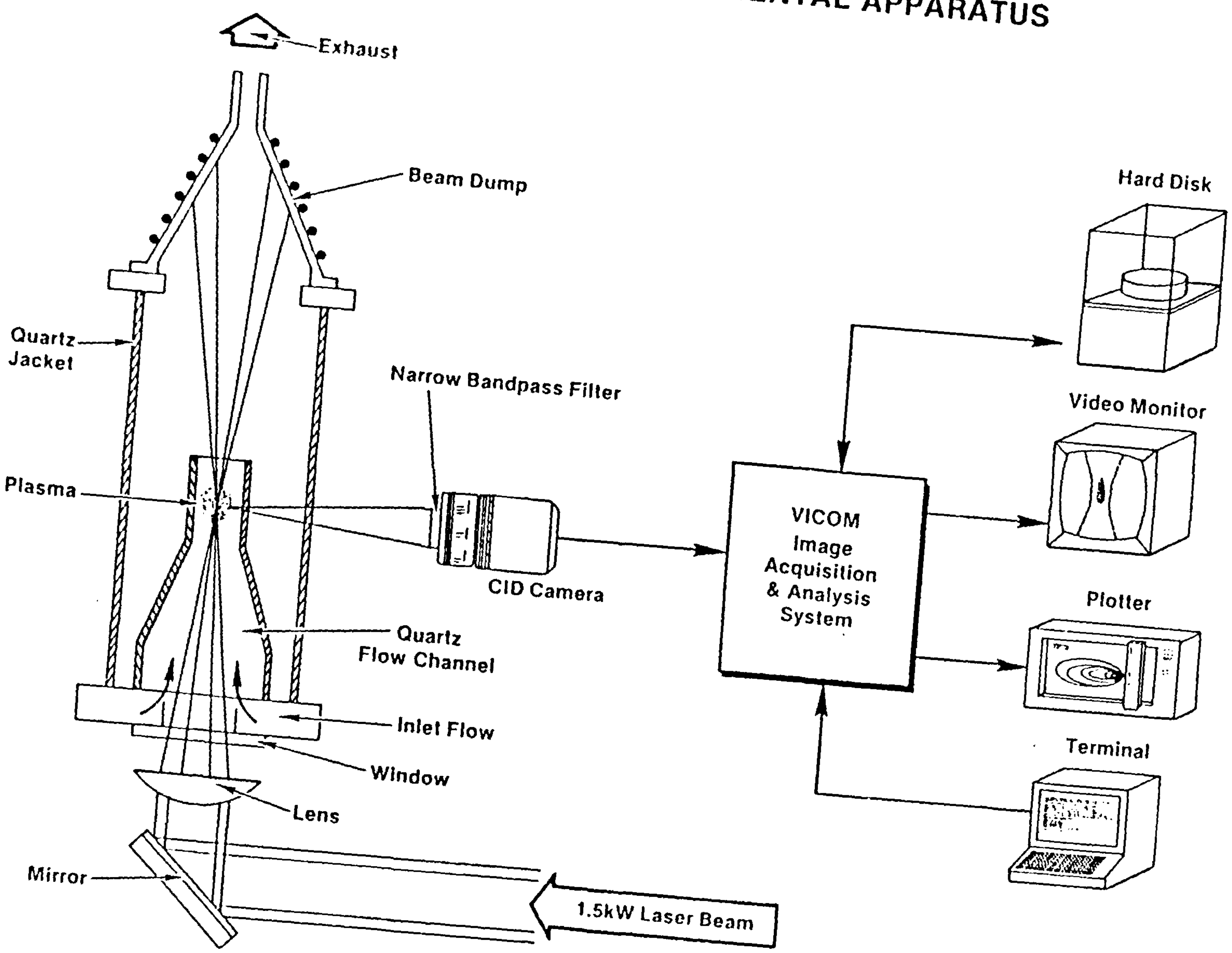
None

Additional Statement

It has become clear that a modification to the chamber must be made in order to separate the transmitted beam power from thermal radiation and convective heating of the gas in order to accurately determine the fractional power absorption of the plasma. This will involve the design and fabrication of a special mirror to close the end of the chamber. Additionally, it appears that the advent of thermoplastic imaging devices make it practical to develop a holographic, real-time interferometer to determine the density of the flowfield in the lower temperature portions of the plasma. We propose that we be allowed to undertake the development of this advanced plasma diagnostic technique with AFOSR support through either an expansion of the current contract or initiation of a separate contract.

FIGURE 1

SCHEMATIC OF THE EXPERIMENTAL APPARATUS



REFERENCES

1. Jeng, San-Mou and Keefer, Dennis R., "Theoretical Investigation of Laser-Sustained Argon Plasmas," J. Appl. Phys. 60(7), pp. 2272-2279, 1 Oct. 1986.

2. Keefer, Dennis R., Smith, L. Montgomery and Sudharsanan, S.I., "Abel Inversion Using Transform Techniques," presented at ICALEO '86 Laser Applications Conference, Arlington, Virginia, Nov. 1986.

3. Keefer, D., Welle, R. and Peters, C., "Power Absorption in Laser-Sustained Argon Plasmas," AIAA-85-1552, Cincinnati, Ohio, Jul. 1985.

4. Welle, R., Keefer, D. and Peters, Carroll, "Energy Conversion Efficiency in High-Flow Laser-Sustained Argon Plasmas," AIAA-86-1077, Atlanta, Georgia, May 1986.

5. Keefer, D., Crowder, H. and Peters, C., "Laser Sustained Argon Plasmas in a Forced Convection Flow," AIAA-85-0388, Reno, Nevada, Jan. 1985.

6. Jeng, San-Mou, Keefer, Dennis R., Welle, Richard and Peters, Carroll, "Numerical Study of Laser-Sustained Argon Plasmas in a Forced Convective Flow," AIAA-86-1078, Atlanta, Georgia, May 1986.

7. Jeng, S.-M. and Keefer, D. R., "Numerical Study of Laser-Sustained Hydrogen Plasmas in a Forced Convective Flow," AIAA-86-1524, Huntsville, Alabama, Jun. 1986.

List of Publications Generated Under This Contract:

1. Keefer, D., Peters, C. and Crowder, H., "A Reexamination of the Laser Supported Combustion Wave," AIAA-83-1444, Montreal, Canada, Jun. 1983.

2. Keefer, D., Elkins, R., Peters, C. and Jones L., "Laser Thermal Propulsion," reprint from Orbit-Raising and Maneuvering Propulsion: Research Status and Needs, edited by Leonard H. Caveny, Vol. 89 of Progress in Astronautics and Aeronautics, 1984.

3. Keefer, D., Crowder, H. and Peters, C., "Laser Sustained Argon Plasmas in a Forced Convection Flow," AIAA-85-Ø388, Reno, Nevada, Jan. 1985.

4. Keefer, D., Welle, R. and Peters, C., ""Power Absorption in Laser-Sustained Argon Plasmas," AIAA-85-1552, Cincinnati, Ohio, Jul. 1985.

5. Keefer, D., Peters, C. and Crowder, H., "A Reexamination of the Laser-Supported Combustion Wave," AIAA Journal, Vol. 23, No. 8, pp. 12Ø8-1212, Aug. 1985.

6. Welle, R. and Keefer, D., "Imagining of Continuum Emission for Diagnostics of Laser Sustained Plasmas," proceedings of 1st International Laser Science Conference, Dallas, Texas, Nov. 1985.

7. Welle, R., Keefer, D. and Peters, Carroll, "Energy Conversion Efficiency in High-Flow Laser-Sustained Argon Plasmas," AIAA-86-1Ø77, Atlanta, Georgia, May 1986.

8. Jeng, San-Mou, Keefer, Dennis R., Welle, Richard and Peters, Carroll, "Numerical Study of Laser-Sustained Argon Plasmas in a Forced Convective Flow," AIAA-86-1Ø78, Atlanta, Georgia, May 1986.

9. Jeng, S.-M. and Keefer, D. R., "Numerical Study of Laser-Sustained Hydrogen Plasmas in a Forced Convective Flow," AIAA-86-1524, Huntsville, Alabama, Jun. 1986.

1Ø. Smith, L. Montgomery and Keefer, Dennis R., "The Fourier Optical Analysis of Aberrations in Focused Laser Beams," proceedings at SPIE's 3Øth Annual International Technical Symposium, San Diego, California, Aug. 1986.

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